R-66

ASTROGEOLOGIC STUDIES

ANNUAL PROGRESS REPORT

July 1, 1963 to July 1, 1964

UNPUBLISHED PRELIMINARY DATA

GPO PRICE $ ______

OTS PRICE(S) $ ______

Hard copy (HC) 2.00

Microfiche (MF) .50

SUMMARY

FACILITY FORM 602

N65 16264 (ACCESSION NUMBER)

(THRU)

35 (PAGES)

1 (CODE)

CR 60509 (NASA CR OR TMX OR AD NUMBER)

30 (CATEGORY)

DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

ASTROGEOLOGIC STUDIES

ANNUAL PROGRESS REPORT

July 1, 1963 to

July 1, 1964

SUMMARY

November 1964

This preliminary report is distributed without editorial and technical review for conformity with official standards and nomenclature. It should not be quoted without permission.

This report concerns work done on behalf of the National Aeronautics and Space Administration.

DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

DISTRIBUTION

	No. of Copies
National Aeronautics and Space Administration Washington, D. C.	
Dr. H. E. Newell Director, Office of Space Sciences and Applications------	10
Mr. O. W. Nicks Director, Lunar and Planetary Programs------------------	1
Mr. R. P. Bryson--	1
Mr. W. B. Foster Director, Manned Space Sciences Division----------------	1
Dr. V. C. Fryklund--------------------------------------	1
Dr. G. E. Mueller Director, Office of Manned Space Flight-----------------	1
Col. Thomas Evans---------------------------------------	1
Mr. D. A. Beattie---------------------------------------	1
Goddard Space Flight Center Greenbelt, Maryland--	2
Dr. H. J. Goett, Director-------------------------------	1
Dr. W. N. Hess--	1
Dr. J. A. O'Keefe---------------------------------------	1
Ames Research Center Moffett Field, California--	2
Mr. H. J. Allen---	1
Dr. C. P. Sonnett---------------------------------------	1
Dr. D. R. Chapman---------------------------------------	1
Mr. D. E. Gault---	1

	No. of Copies
Jet Propulsion Laboratory California Institute of Technology Pasadena, California--	6
Dr. W. H. Pickering, Director---------------------------	1
Dr. Robert Meghreblian----------------------------------	1
Dr. R. G. Brereton--------------------------------------	1
Mr. H. R. Lawrence--------------------------------------	1
Mr. Justin Rennilson------------------------------------	1
Dr. Thomas Vrebalovich----------------------------------	1
Manned Spacecraft Center Houston, Texas--	2
Dr. R. R. Gilruth, Director-----------------------------	1
Mr. Maxime Faget--	1
Mr. W. E. Stoney, Jr.-----------------------------------	1
Mr. J. M. Eggleston-------------------------------------	1
Mr. J. E. Dornbach--------------------------------------	1
George C. Marshall Space Flight Center Huntsville, Alabama---	2
Dr. Wernher von Braun, Director-------------------------	1
Dr. Ernst Stuhlinger------------------------------------	1
Mr. Herbert Schaefer------------------------------------	1
Mr. E. E. Dungan--	1
Mr. H. P. Gierow--	1
Mr. Gene Oliver---	1
Mr. David Paul--	1

	No. of Copies
U.S. Geological Survey, Washington, D. C.--------------------	30
Branch of Astrogeology (including master)---------------	75
Dr. P. H. Abelson Director, Geophysical Laboratory Carnegie Institution, Washington, D. C.---------------------	1
Dr. C. S. Beals Dominion Observatory Ottawa, Canada---	1
Dr. I. S. Bowen Director, Mt. Wilson and Palomar Observatories Mt. Wilson, California--	1
Professor Harrison Brown Department of Geological Sciences California Institute of Technology Pasadena, California--	1
Mr. William Cannell Aeronautical Chart and Information Center Lowell Observatory, Flagstaff, Arizona----------------------	1
Mr. R. W. Carder Aeronautical Chart and Information Center St. Louis, Missouri---	1
Dr. Audouin Dollfus Observatoire de Paris Meudon, France---	1
Dr. W. D. Ehmann Department of Geology University of Kentucky Lexington, Kentucky---	1
Colonel J. G. Eriksen Aeronautical Chart and Information Center St. Louis, Missouri---	1

DISTRIBUTION--Continued

	No. of Copies
Professor Laurence Frederick Director, Leander McCormick Observatory University of Virginia Charlottesville, Virginia	1
Dr. J. S. Hall Director, Lowell Observatory Flagstaff, Arizona	1
Dr. J. M. Harrison Geological Survey of Canada Ottawa, Canada	1
Professor H. H. Hess Department of Geology Princeton University Princeton, New Jersey	1
Dr. A. A. Hoag Director, U.S. Naval Observatory Flagstaff, Arizona	1
Dr. Zdenek Kopal Department of Astronomy University of Manchester Manchester, England	1
Professor G. P. Kuiper Director, Lunar and Planetary Laboratory University of Arizona Tucson, Arizona	1
Professor G. J. F. MacDonald Institute of Geophysics University of California Los Angeles, California	1
Dr. A. B. Meinel Director, Steward Observatory University of Arizona Tucson, Arizona	1

	No. of Copies
Professor B. C. Murray Department of Geological Sciences California Institute of Technology Pasadena, California	1
Dr. K. S. Pierce, Director, Kitt Peak National Observatory Tucson, Arizona	1
Mr. Herbert Reich Northrup Space Laboratories Hawthorne, California	1
Dr. Jean Rösch Directeur, Observatoire du Pic-du-Midi Pic-du-Midi, France	1
Dr. J. W. Salisbury Cambridge Air Force Research Laboratories Bedford, Massachusetts	1
Dr. E. A. Steinhoff Air Force Missile Development Center Holloman A.F.B., New Mexico	1
Professor H. C. Urey Scripps Institute of Oceanography University of California La Jolla, California	1
Dr. S. Vasilevskis Lick Observatory Mt. Hamilton, California	1
Dr. F. L. Whipple Director, Smithsonian Astrophysical Observatory Washington, D. C.	1
Dr. A. E. Whitford Director, Lick Observatory Mt. Hamilton, California	1

CONTENTS

	Page
Introduction	1
Summary of Part A	6
Part B	13
Part C	19

INTRODUCTION

This Annual Report is the fifth of a series describing the results of research conducted by the U.S. Geological Survey on behalf of the National Aeronautics and Space Administration. This report, which covers the period July 1, 1963 to July 1, 1964, is in three volumes corresponding to three main areas of research: Part A, Lunar and Planetary Investigations; Part B, Crater and Solid State Investigations; and Part C, Cosmic Chemistry and Petrology; and a map supplement. An additional volume presents in abstract form summaries of the papers in Parts A, B, and C.

The major long-range objectives of the astrogeologic studies program are to determine and map the stratigraphy and structure of the Moon's crust, to work out from these the sequence of events that led to the present condition of the Moon's surface, and to determine the processes by which these events took place. Work being carried out that leads toward these objectives includes a program of lunar geologic mapping; studies on the discrimination of geologic materials on the lunar surface by their photometric, polarimetric, and infrared properties; field studies of structures of impact, explosive, and volcanic origin; laboratory studies on the behavior of rocks and minerals subjected to shock; and study of the chemical, petrographic and physical properties of materials of possible lunar origin and the development of special techniques for their analysis.

Part A: Lunar and Planetary Investigations contains (with the map supplement), the preliminary results of detailed geologic mapping on a 1:1,000,000 scale of five new quadrangles in the equatorial belt of the Moon. Several major stratigraphic units in the Imbrian and pre-Imbrian systems are described by the authors who have studied these quadrangles. Four papers discuss problems of origin and evolution of various types of craters and features associated with the craters such as rilles and rays. As a part of the lunar geologic investigations, detailed studies of the infrared emission and reflected visible radiation from the Moon are in progress; a description of a systematic program of photoelectric and photographic photometry and the relation of the visible lunar photometric function to the infrared emission are given in this report.

Part B: Crater Investigations contains the results of field and laboratory studies of shock and crater phenomenology. The effect of shock on rock materials forms the subject of four reports: (1) the shock wave synthesis of stishovite, (2) the physical properties of shock-formed plagioclase from a meteorite, (3) some characteristics of natural glasses and high pressure phases that serve as evidence for their origin by meteorite impact, and (4) the effect of shock on the radiogenic argon content of granite. One report concerns the shock equation of state on two rocks from Meteor Crater, Arizona. Two reports deal with experimental craters: one is concerned with a field study of craters formed by missile impact and the other with a study of craters formed in porous-cohesive targets by hypervelocity projectiles. Work on three naturally formed craters is reported. This includes a new topographic map of Meteor Crater, Arizona, made to serve as a base for the geologic work; a geologic study of a meteorite crater and associated rays of ejecta at Henbury, Australia; and field and laboratory studies of the Flynn Creek structure, Tennessee.

Part C: Cosmic Chemistry and Petrology includes reports on aerodynamic features, geologic occurrences, chemical composition and metallic spherules of tektites, methods of chemical analysis of tektites and other extraterrestrial material, and the luminescence of achondritic meteorites.

The following reports were published during the reporting period July 1, 1963 to July 1, 1964:

Annel, Charles, Cuttitta, Frank, Chao, E. C. T., and Fletcher, J. D., 1964, Minor elements in selected Australasian tektites [abs.]: Am. Geophys. Union Trans., v. 45, no. 1, p. 81.

Chao, E. C. T., 1963, The petrographic and chemical characteristics of tektites, in O'Keefe, J. A., ed., Tektites: Chicago, Univ. Chicago Press, p. 51-94.

Chao, E. C. T., Dwornik, E. J., and Littler, Janet, 1964, New data on the nickel-iron spherules from southeast Asian tektites and their implications: Geochim. et Cosmochim. Acta, v. 28, no. 6, p. 971-980.

Cuttitta, Frank, Chao, E. C. T., Carron, M. K., and Littler, Janet, 1964, Some physical properties and the major chemical composition of selected Australasian tektites [abs.]: Am. Geophys. Union Trans., v. 45, no. 1, p. 81.

Gault, D. E., Heitowit, E. D., and Moore, H. J., 1963, Some observations of hypervelocity impacts with porous media: U. S. Natl. Aeronautics and Space Adm. TM X-54,009, 35 p.

Gault, D. E., Heitowit, E. D., and Moore, H. J., 1964, Some observations of hypervelocity impacts with porous media, in Salisbury, J. W., and Glaser, P. E., eds., The lunar surface layer--materials and characteristics: New York, Academic Press, p. 151-178.

Lugn, R. V., 1964, Photogrammetric mapping of experimental craters: Photogramm. Eng., v. 30, no. 1, p. 55-58.

Moore, H. J., Gault, D. E., and Lugn, R. V., 1963, Experimental impact craters in basalt: Am. Inst. Mining Metall. Eng. Trans., v. 226, no. 3, p. 258-262.

Moore, H. J., MacCormack, R. W., and Gault, D. E., 1963, Fluid impact craters and hypervelocity--High-velocity impact experiments in metals and rocks, in Proceedings of the Sixth symposium on hypervelocity impact, Cleveland, Ohio, April 30, May 1, 2, 1962: Cleveland, Firestone Tire & Rubber Co., v. 2, pt. 2, p. 367-399.

Rose, H. J., Jr., Cuttitta, Frank, Carron, M. K., and Brown, Robena, 1964, Semimicro X-ray fluorescence analysis of tektites using 50-milligram samples: Art. 157, in U.S. Geol. Survey Prof. Paper 475-D, p. D171-D173.

Senftle, F. E., and Hoyte, A. F., 1964, Resistivity and viscosity of tektites [abs.]: Am. Geophys. Union Trans., v. 45, no. 1, p. 81.

Senftle, F. E., Thorpe, A. N., and Lewis, R. R., 1964, Magnetic properties of nickel-iron spherules in tektites from Isabela, Philippine Islands: Jour. Geophys. Research, v. 69, no. 2, p. 317-324.

Shoemaker, E. M., Gault, D. E., Moore, H. J., and Lugn, R. V., 1963, Hypervelocity impact of steel into Coconino sandstone: Am. Jour. Sci., v. 261, no. 7, p. 668-682.

Skinner, B. J., and Fahey, J. J., 1963, Observations on the inversion of stishovite to silica glass: Jour. Geophys. Research, v. 68, no. 19, p. 5595-5604.

Taylor, H. P., Jr., Duke, M. B., Silver, L. T., and Epstein, S., 1964, Oxygen isotopic studies of minerals in stony meteorites [abs.]: Am. Geophys. Union Trans., v. 45, no. 1, p. 112.

Thorpe, A. M., and Senftle, F. E., 1964, Submicroscopic spherules and color of tektites: Geochim. et Cosmochim. Acta, v. 28, no. 6, p. 981-994.

Walter, L. S., and Carron, M. K., 1964, Vapor pressure and vapor fractionation of silicate melts of tektite composition: Geochim. et Cosmochim. Acta, v. 28, no. 6, p. 937-951.

Summary of Part A

Geologic mapping of the Moon at a scale of 1:1,000,000 forms the base for the lunar investigations of the Geological Survey for the National Aeronautics and Space Administration. The geologic maps of the Kepler and Letronne quadrangles have been published in color (fig. 1). Preliminary geologic maps of the following quadrangles were transmitted to NASA previously: Copernicus by E. M. Shoemaker and R. J. Hackman, Apennine Mountains by R. J. Hackman, Aristarchus by H. J. Moore, Timocharis by M. H. Carr, Riphaeus by R. E. Eggleton, Hevelius by J. F. McCauley, and Mare Humorum by S. R. Titley. Maps accompanying this report include Ptolemaeus by Harold Masursky, Pitatus by S. R. Titley, Theophilus by D. J. Milton, Mare Vaporum by D. E. Wilhelms, and Grimaldi by J. F. McCauley. Mapping is in progress in the Mare Undarum, Langrenus, Julius Caesar, Taruntius, Mare Serenitatus, Columbo, Macrobius, Seleucus, Purbach, Altai Scarp, and Fracastorius quadrangles, and these will be completed in fiscal year 1965. Although base maps for Cleomedes, Petavius, and Byrgius will not be available, the geology of these quadrangles will be compiled on photographic overlays.

Maps forwarded to date cover more than a million and a half square miles or four million square kilometers. By the end of fiscal year 1965, the maps of the lunar equatorial belt, amounting to more than three million square miles, should be completed.

A preliminary geologic map of the Mare Vaporum quadrangle, which lies within the peripheral belt of structures related to the Mare Imbrium basin, has been completed by D. E. Wilhelms. Major structural elements within the

 (page 6a follows)

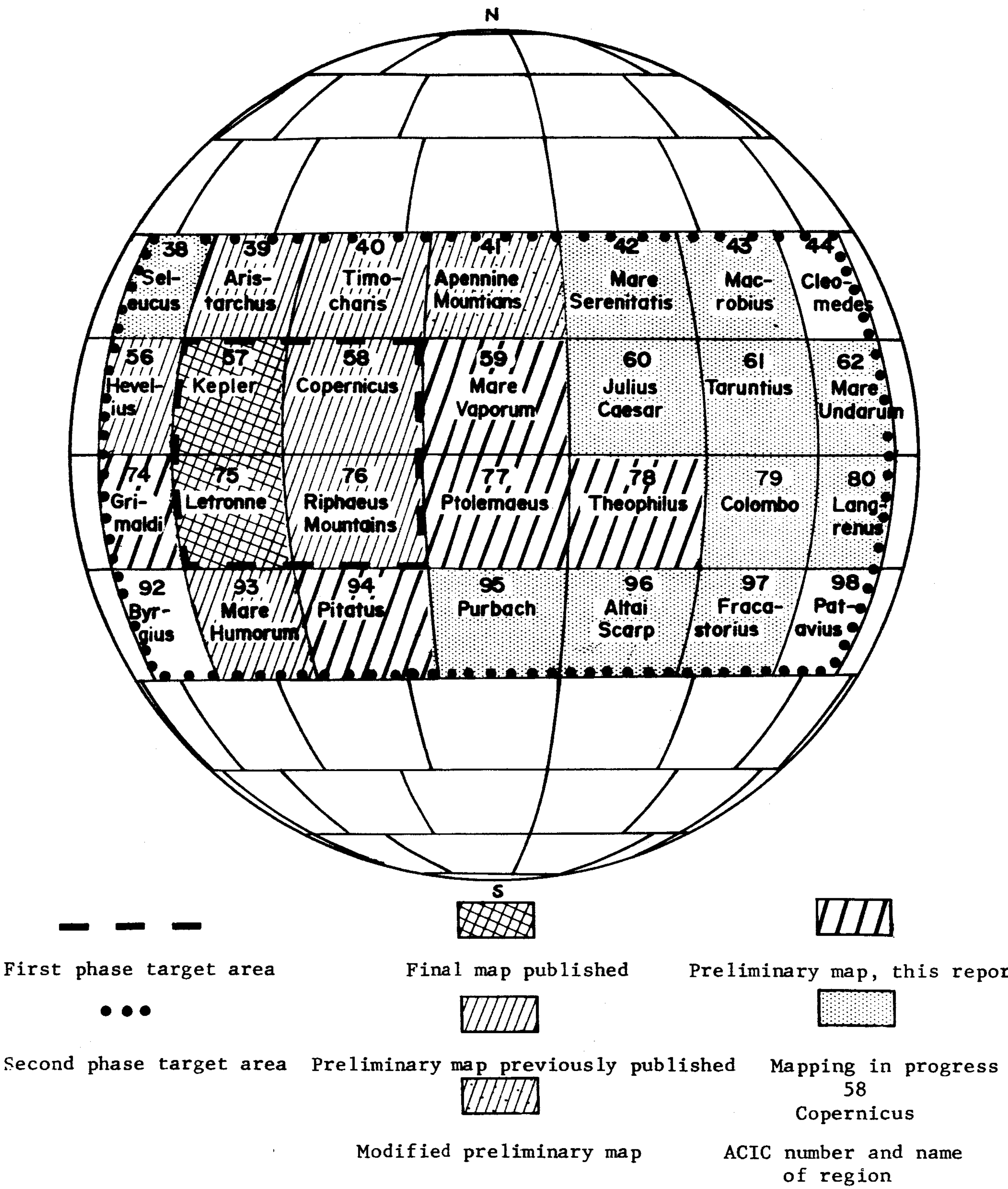

Figure 1. Index map of the Moon showing status of geologic mapping at a scale of 1:1,000,000.

quadrangle--mare depressions and terra highs--are interpreted as synclines and anticlines, which are roughly concentric with the Mare Imbrium basin and in places are modified by faults. Most of the terra area in the quadrangle is deformed by troughs and ridges of the "Imbrian sculpture" radial to the basin, and is covered by the Fra Mauro Formation, which is interpreted as ejecta from the Mare Imbrium basin. Some of the structure present may have been produced by interaction of deforming forces at the time the Mare Imbrium basin was formed on older structures related to the basin of Mare Serenitatis. Still other structures not obviously related to the Mare Imbrium basin, such as the Triesnecker rille system, may have been formed by isostatic readjustment of the lunar crust subsequent to the Imbrian event. Part of Hyginus Rille is aligned with Imbrian sculpture.

A complex stratigraphic sequence has been mapped in the terra of the western Theophilus quadrangle by D. J. Milton. Crater rims and other terrain cut by prominent northwest-southeast trending scarps (Imbrian sculpture) is believed to be pre-Imbrian. Terrain with a much finer grained texture of small rounded hills and valleys elongated in the same direction is correlated with the Fra Mauro Formation of Apenninian age. This is overlain by a smooth-surfaced plains-forming unit that partially fills basins. Adjacent higher areas with subdued relief are probably underlain by a thinner deposit of the same material. This material is tentatively considered to be of Apenninian age; it may, however, be Archimedian. A plateau-forming unit has a broadly rolling, smooth surface with some steep-walled irregular depressions. This unit, in contrast to the plains-forming unit, does not tend to occupy basins but forms broad plateaus with the underlying relief completely concealed. The age of the plateau-forming unit is uncertain; it may be an age equivalent of the plains-forming unit.

Preliminary geologic mapping of the Grimaldi quadrangle has been completed by J. F. McCauley. This mapping establishes the stratigraphic relationships between the regional materials surrounding the Mare Orientale and Mare Humorum basins. North of the crater Fontana, smooth textured, high albedo material of the Cordillera Group (associated with the Orientale basin) overlies darker, rougher textured material of the Humorum Group, which clearly is younger than the Humorum basin.

Very dark mare material is extensive within the area. This material is characterized by a low spatial density of craters and a general lack of superimposed rays, suggesting that it may be younger than the mare material typical of the Procellarum Group.

Trajectories of objects producing Copernicus ray material on the crater Eratosthenes have been studied by M. H. Carr. In the region of Eratosthenes, areas lacking Copernicus ray material are principally on slopes facing away from Copernicus. Assuming the absence of ray material in these areas is due mainly to topographic shielding, trajectories may be computed for objects ejected from Copernicus to produce secondary craters and rays in Eratosthenes. Mean values of 7 degrees for the ejection angle and 1.1 km/sec. for the ejection velocity are found.

A possible volcanic complex near the Harbinger Mountains of the Moon has been investigated by H. J. Moore. Abundant hills, craters and rimae (rilles) are present just west of the Harbinger Mountains. The close association of the craters and rimae suggest that the area is a volcanic complex. These lunar craters resemble terrestrial maars and rampart craters, and one is like a caldera. Lunar craters that are similar to maars and rampart craters are larger than their suggested terrestrial counterparts.

Some of the sinuous rimae are crater chains; not all sinuous rimae can be the result of erosion by nuées ardentes as suggested by other workers.

The history of the temperature regime around the crater Timocharis was computed by M. H. Carr, assuming an impact origin for the crater and shock equations of state similar to basalt for the target and projectile. For impact velocities greater than 8 km/sec, temperatures sufficiently high for melting extend a distance of 6 km below the crater. At lower impact velocities, melting temperatures are not reached. The transient high temperature source at the surface, immediately after impact, has an insulating effect so that lunar internal heat cannot escape to the surface. This causes elevation of temperature at depths far below the impact-induced temperature anomaly. Lowering of the thermal conductivity near the surface by impact brecciation will also have an insulating effect. The temperature rise at depth may be great enough to produce melting and volcanism long after the impact event.

Infrared emission from the illuminated Moon is being investigated by Kenneth Watson. Pettit and Nicholson observed that the infrared emission of the Moon near zero phase angle at the limb along the lunar equator exceeds the emission to be expected from a Lambert emitter. Pettit and

Nicholson suggested that this excess emission at the limb is due entirely to the fact that at full Moon no shadows are seen and only illuminated surfaces contribute to the emission. This can not be valid at the scale of lunar mountains and valleys, however. The average slopes at this scale are much too low to produce appreciable departure from Lambert emission in the infrared. On the other hand, reradiation between surfaces on a scale less than a few centimeters tends to produce uniform emission that follows the Lambert law.

Computations of the variation of the total visible reflectivity as a function of angle of incidence, for Hapke's "fairy castle" model, show a Lambert emitter would lead to less emission in the infrared at the limb than is adequate to result in infrared limb darkening. The observed excess emission of the limb may be caused by either (1) roughness on a scale between a centimeter and meter and (2) non-Lambert emission from individual surface elements. In the first case, roughness may possibly be related to the high spatial density of secondary craters on the lunar surface.

Existing high speed photographic systems employed in lunar photographic photometry have, for the most part, contained large inherent errors. These errors can be traced to (1) shutters with variable speeds and (2) processing systems which employ nonuniform agitation of developing solutions. H. Pohn has designed a high speed photometric camera which largely overcomes shutter errors by utilization of adjustable slits which are pulled along mated teflon ways. This system is coupled with a plate processing system which holds the internal variations in plate response to about 3% of mean plate density. A camera employing the new design features will be used on the

Geological Survey's 30-inch telescope to obtain photographs for a photoelectrically calibrated photographic atlas of the Moon.

S. R. Titley discusses the stratigraphic and structural relationships in the Pitatus quadrangle and adjacent parts of the Moon. Preliminary geologic mapping has disclosed a complex sequence of events in this region that include basin formation, regional deposition, and tectonic activity. Certain critical structural and stratigraphic relationships have been observed and tentative interpretations can be made concerning relative ages of the Mare Humorum, Mare Nubium, and Mare Imbrium basins. Ejecta(?) from the Mare Humorum basin makes up most of the old upland exposures around the west edge of Mare Nubium and, in the northwest part of the quadrangle, may underlie the Fra Mauro Formation, which is ejecta from the Mare Imbrium basin. Structural relationships on the west edge of the quadrangle suggest that the circumferential structures about Mare Humorum are older than those about Mare Nubium.

S. R. Titley and R. E. Eggleton describe an extensive hummocky deposit around the Mare Humorum basin. This material, which is uniform in its subdued topographic characteristics and normal albedo, is distributed about Mare Humorum. It occurs now as isolated patches and tongues, but it is believed at one time to have surrounded Mare Humorum as a nearly continuous blanket. In many respects it is similar to hummocky Fra Mauro Formation. The hummocky material about Mare Humorum has an extent and distibution that is comparable with the extent and distribution of the Fra Mauro Formation when the relative sizes of the Humorum and Imbrium basins are considered. The material has all the characteristics of an extensive ejecta blanket and appears to be derived from the Mare Humorum basin.

D. E. Wilhelms has initiated a program of lunar polarimetry with a Lyot visual polarimeter mounted on the 12-inch refractor of Lick Observatory. Preliminary results indicate that polarization of areas on the lunar surface 8 kilometers in diameter can be measured under conditions of good seeing with these instruments.

Harold Masursky reports on the isostatic rebound of lunar craters and a reinterpretation of Ptolemaeus. The rebound of lunar craters of a similar size to Ptolemaeus indicates that the cover on the floor of the crater may be very thin, that is, only thick enough to have buried the central peaks. The remainder of the initial crater has been obliterated by respringing of the crater floor.

Summary of Part B

P. S. DeCarli and D. J. Milton have separated small amounts of stishovite from explosively shocked sandstones, novaculite, and single crystal quartz. Estimated peak pressures for the syntheses ranged from 150 to 280 kilobars and shock temperatures from 150 to 300°C. Coesite was not detected in any of the samples. This suggests that quartz can invert during shock to a short-range-order phase with sixfold coordination, a small part of which may develop the long-range order of stishovite. During the more protracted decay of the pressure pulse through the stability field of coesite accompanying meteorite crater formation, a part of the short-range-order phase may invert to coesite.

M. B. Duke investigated natural plagioclase glass from the Shergotty meteorite and found its average composition to be about An_{49}. Its density is variable within a range near 2.57 g/cc . The refractive index ranges from 1.539 to 1.554 and is distinctly higher than the indices of synthetic plagioclase glass in the same compositional range. Experiments show that the refractive index can be markedly reduced by heating for a few minutes at temperatures as low as 450°C. These data put limits on the thermal history of the meteorite following the formation of the plagioclase glass.

M. H. Carr measured shock pressures and shock wave speeds in various specimens by means of a strain gage technique. The Hugoniot curve of Coconino Sandstone was determined for pressures ranging from 0 to 150 kilobars. For this pressure range the shock wave speeds ranged from 3.0

to 4.0 km/sec. For similar shock energies in Moenkopi Sandstone, an elastic precursor with a speed of 3.1 km/sec and a shock wave with speeds ranging from 2.5 to 2.9 km/sec are generated.

P. Signer compared the argon contacts of unshocked and strongly shocked granites from the Ries crater, Germany, and found that the shocked sample contains far less radiogenic argon than the unshocked one. New amorphous phases formed by shock absorb much greater quantities of atmospheric argon than their parent crystalline phases.

E. C. T. Chao has described selective shock transformations of minerals in rocks from known and probable meteorite craters, and has shown that their special characteristics may be used as evidence of meteorite impact. The transformations are of two distinct types: (1) from a crystalline phase of complex chemical composition to glass of the same composition and (2) from a crystalline phase of simple chemical composition to its high pressure and high density polymorph. Mineral phase transformations of the first type, formed at high pressure and probably low temperatures, are observed in impact metamorphosed sandstones from the Henbury craters of Australia and in biotite granites, gneisses, and schists in suevite from the Ries crater. Transformations from a low density to a high density polymorph, such as from quartz to coesite or stishovite, occurred in impact metamorphosed sandstones of Meteor Crater, Arizona, and the Wabar crater, Saudi Arabia; in the biotite granite gneisses of the Ries crater; and in metamorphic rocks of the Lake Bosumtwi crater, Ghana.

A study by H. J. Moore, R. Kachadoorian and H. C. Wilshire of craters produced by the impact of missiles extends our knowledge of experimental impact craters to those produced by projectiles with large kinetic energies (2.3×10^{15} ergs). The amount of material displaced during crater formation by projectile impact is nearly the same as the amount of material displaced during crater formation by chemical explosives with small scaled depths of burial when the kinetic energy of the projectile (corrected for the angle of impact) is equal to the equivalent energy of TNT of the chemical explosive.

H. J. Moore, D. E. Gault, E. D. Heitowit, and R. V. Lugn have investigated craters produced by hypervelocity impacts in porous cohesive targets. The craters show a distinct change in shape with the porosity of the target. Depth-to-diameter ratios increase from 1 to 5 for non-porous targets such as basalt to about 1 to 1 for porous targets such as pumice.

The ejecta from craters in all target types are composed chiefly of undeformed rock fragments. Ejecta from craters in basalt have abundant, large fragments, whereas ejecta from weakly-bonded sand targets are composed chiefly of grains with the same size as the target sand. The ejecta from pumice have large amounts of fragments near the size of the cell walls between the vesicles. Significant parts of the ejecta from craters in pumice are composed of complex aggregates of crushed pumice and glass fibers. The aggregates resemble volcanic ash.

Craters in weakly-bonded sand targets are larger than craters in basalt. Craters in pumice are smaller than those in weakly-bonded sand and basalt. In addition, craters in fine-grained, weakly-bonded sand targets are smaller than those in coarse-grained sand targets. Application of a defect theory of strength reduces the scatter of the data between sandstone and weakly-bonded sand targets.

Finally, it is shown that the shapes and ejecta of recent small lunar craters may be used to recognize cohesion of lunar surface materials. It is postulated that the uppermost part of the lunar surface could be composed of a material similar to volcanic ash which resulted from micrometeoroid bombardment.

R. M. Batson has completed a preliminary 1:4,600 scale topographic map of Meteor Crater by photogrammetric methods. Larger scale mapping of the crater has been undertaken to provide a suitable base for the detailed geologic maps.

D. J. Milton and F. C. Michel mapped the only terrestrial crater known to have associated rays of ejecta similar to those around lunar craters. Crater No. 3 of the Henbury crater field, Northern Territory, Australia, is a roughly circular crater about 200 feet in diameter with 15 feet relief from floor to rim crest, and 5 feet from the surrounding surface to the crest. It is formed in alternating beds of well-cemented sandstone and weak shale dipping about 35°, overlain by a variable thickness of pediment gravel. Beds striking into the walls of the crater are deformed, predominantly by folding about approximately vertical axes. Fragments from the several units in the bedrock occur in separate areas in the throwout around the crater. Some of these areas are elongate and approximately radial to the crater, resembling the rays around lunar craters. In general the distance to which fragments were thrown out is inversely proportional to the distance of the point of origin from the center of the crater. Ejecta from two of the beds form loops that are connected at either end to the outcrop of the bed in the crater wall and are symmetrical about a radial line from the center of the crater at right angles to the strike of the bedrock. The larger loop extends over 200 feet from the crater. It is much smaller and also narrower in proportion to its radial extent from the crater than would be expected for a ray loop developed in accordance with a model of crater ballistics based on a uniform density of energy within the shock front. The effective energy density decreased as a function of the radius of the shock front at a greater rate than by a simple shock propagation model, probably because the finite strength of the bedrock is not considered in such a model.

New data on several critical problems have been derived from recent field studies of the southeastern rim of the Flynn Creek structure by D. J. Roddy. The southeastern rim consists of a structurally complex sequence of Upper Ordovician rocks, and contains what appears to be a part of the ground surface that existed immediately before the deformation. A large mass of breccia covers the original ground surface and is preserved in a down-faulted block. Field and laboratory studies of the rocks underlying this surface strongly suggest that they are Upper Ordovician in age and can probably be assigned to the Richmond Group.

Calculations of the stratigraphic thicknesses in the southeastern rim suggest that not more than 60 meters of strata have been removed by erosion after the structure was formed and before later sediments were deposited. The maximum age of the Flynn Creek structure is therefore Late Ordovician. The minimum age is early Late Devonian.

The pre-deformation lithostatic pressures have been calculated for different stratigraphic levels on the basis of the pre-deformation ground level; certain comparisons in possible mechanics of deformation by high gas pressures and by meteorite impact can then be made.

A preliminary search did not reveal the presence of the high pressure silica polymorphs coesite and stishovite that have been found in some known meteorite impact structures. Geophysical studies by S. Biehler and D. J. Roddy indicate that there is no large magnetic anomaly associated with the structure, such as might be expected if an igneous plug were present below the structure.

Summary for Part C

Studies in cosmic chemistry and petrology presented in this Annual Report include (1) geological distribution and physical and chemical properties of tektites, (2) investigations of microanalytical techniques for analyzing milligram and sub-milligram quantities of tektites, meteorites and, eventually, returned lunar samples, and (3) petrology and chemistry of meteorites.

A moldavite from Slavice, Czechoslovakia, was found by E. C. T. Chao to show indirect evidence of aerodynamic heating and ablation. No direct or indirect evidence for heating or ablation of moldavites had previously been recognized. The indirect evidence consists of the keel left by spallation of the heated and strained glass of the leading surface of a teardrop-shaped tektite. The moldavite's keel is identical to those of australite indicators (partially spalled tektites). For moldavites, this is the first evidence bearing on their probable entry velocity into the Earth's atmosphere, which must have been greater than about 5 km/sec in order to cause ablation.

Field geologic studies of Australasian tektite occurrences by E. C. T. Chao indicate that they are younger than middle Pleistocene in age, but more accurate age determinations can not be made with present geologic data. The geologic ages are consistent with K/Ar data which indicate ages on the order of 700,000 years for the Australasian tektites. The tektites are found primarily in laterite soils, where transportation of the tektites probably has been minimal, and in gravel deposits, where re-working and transportation of tektites has probably occurred. The maximum number of tektites in the Australasian strewnfield is estimated to be about 2×10^{13} on the basis of the areal density of tektites in places where re-working is improbable. From estimates of the number of tektites concentrated by fluvial transportation in the Manila Bay area of the Philippine Islands, the minimum number of tektites is estimated to be about 4×10^{9} for the entire strewnfield. No terrestrial impact crater capable of producing the Australasian tektites has been discovered.

New chemical analyses for major elements in Australasian tektites reported by F. Cuttitta, M. K. Carron, and E. C. T. Chao, show considerable overlapping of silica contents of indochinites, philippinites, javanites and australites. The analyses show gross similarities of chemical composition, particularly for the alkalis, for all the Australasian tektites, and FeO varies inversely with respect to SiO_2 in each tektite group. The chemical similarities are consistent with a single origin for the Australasian tektites.

The detailed analyses show systematic differences between the philippinite-australite and indochinite-javanite groups of tektites. The philippinite-australite group is marked by CaO greater than MgO and an inverse relation of Al_2O_3 with silica content, whereas the indochinite-javanite group has less CaO than MgO and no apparent relationship between Al_2O_3 and SiO_2. Minor element data showed that the Co, Cr, and Ni contents of philippinites and australites are distinctly higher than in indochinites and javanites. More tektite analyses are underway to attempt to define patterns of regional compositional variations of Australasian tektites, which could provide useful data concerning the lunar or terrestrial origin of tektites.

C. Annell has obtained emission spectrographic analyses for Al, Ca, Fe, Mg, and Ti by the rotating disc-high voltage spark and the gas controlled arc methods with solutions for samples weighing 1-2 mg. The two different solution methods give similar precision and accuracy but the rotating disc method is 3 to 5 times more sensitive and has wider application to the study of small quantities of silicate minerals.

Working curves for the spectrographic determination of Na and K by the totating disc-high voltage spark method also have been obtained by Annell. As little as 0.1 percent Na and 0.3 percent K now can be determined in silicate samples weighing 1 to 2 mg.

Preliminary applications of the laser microprobe for emission spectrographic analysis and neutron activation analysis of spherules from Philippine tektites by F. Cuttitta, E. C. T. Chao, and C. Annell indicate the presence of siderophile and chalcophile elements such as Mo, As, and Ir. These minor elements are generally much more abundant in iron meteorites than in most silica-rich rocks. The qualitative neutron activation analysis, which is the first step in a program of quantitative activation analysis, gives further indication of the meteoritic origin of metallic spherules in tektites.

D. B. Tatlock compared 55 older analyses of Australasian tektites with 110 modern precisely monitored analyses and found that more than half of the older alkali and titania determinations are decidedly inaccurate and misleading. Deviations of the older analyses from the restricted values of the modern analyses are comparable to the imprecisions shown by early analyses of G-1 granite and W-1 diabase. This suggests that a high percentage of older alkali and titania analyses, such as those of Washington's tables, are of questionable quality.

A mineral that luminesces red under UV irradiation in the Norton County enstatite achondrite meteorite has been identified as forsterite by M. B. Duke and B. A. Tryba. Low abundance of forsterite in the meteorite means that the luminescent efficiency of the total meteorite is very low. This appears to eliminate UV-excited enstatite achondrite material as a possible lunar red fluorescent material. Electron-excited luminescence of synthetic diopside shows the major role played by minor element contents of the mineral. Pure diopside luminesces blue; Mn - bearing diopside, red; Ti - diopside, orange; and Ni - diopside, green.